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CHANNEL WAVEGUIDE STUDY

J. M. Hammer, et al

RCA Laboratories

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The objective of this program was the study and development of directional coupler modulators based on the use of the $LiNb_xTa_{1-x}O_3$ waveguide system developed at RCA Laboratories. The program has resulted in a broader understanding of the problems associated with these devices and the observation of actual coupling modulation.

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In addition, an approximate closed form expression for the cut-off conditions and propagation constants of diffused stripe guides was determined and compared with observations.

In the course of the program, a number of physical effects associated with the production of diffused LNT stripe guides and couplers were observed. These effects include the formation of a ridge during the diffusion and the observation of very large surface diffusion (sideways diffusion) in y-plates but much smaller surface diffusion in x-plates. Such lateral diffusion effects combined with the formation of a ridge which is more or less bounded by the initial Nb pattern can clearly play a strong or even dominant role in the operation of devices which depend on confinement in both transverse dimensions as do the stripe guides of interest here.

The effect of this spread on the operation of stripe guides is discussed, and experimental observations on stripe guides and stripe couplers are described.

We summarize the expected operation of directional coupling modulators and analyze the effect that constructional tolerances have on the quality of switching that may be obtained in actual devices.

PREFACE

This Final Report, prepared by RCA Laboratories, Princeton, NJ 08540, describes work performed in the Physical Electronics Research Laboratory, G. D. Cody, Director. The Project Supervisor is B. F. Williams and the Project Scientist is J. M. Hammer. Others who participated in the research and the writing of this report are W. Phillips and C. C. Neil. This report was submitted in draft form in December 1975.

The Navy Project Monitor is T. G. Giallorenzi, Code 5500. This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by ONR under Contract No. N00014-75-C-0078.

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I. INTRODUCTION

The objective of this program was the study and development of directional coupler modulators based on the use of the $LiNb_xTa_{1-x}O_3$ waveguide system developed at RCA Laboratories [1]. The program has resulted in a broader understanding of the problems associated with these devices and the observation of actual coupling modulation in one sample. In addition, an approximate closed form expression for the cut-off conditions and propagation constants of diffused stripe guides was determined and compared with observations.

In the course of the program, a number of physical effects associated with the production of diffused LNT stripe guides and couplers were observed. These effects include the formation of a ridge during the diffusion and the observation of very large surface diffusion (sideways diffusion) in y-plates but much smaller surface diffusion in x-plates. Such lateral diffusion effects combined with the formation of a ridge which is more or less bounded by the initial Nb pattern can clearly play a strong or even dominant role in the operation of devices which depend on confinement in both transverse dimensions as do the stripe guides of interest here.

In this final report, our observations of surface diffusion and ridge formation are described in Section III. Briefly, the surface of the LNT guide is raised by an amount equal to approximately twice the initial niobium thickness. The lateral spread of Nb in y-plates is approximately 20 times the diffusion depth while the spread in x-plates appears to be less than the resolving power of our measurements.

The effect of this spread on the operation of stripe guides is discussed in Section IV, and experimental observations on stripe guides and stripe couplers are described in Section V.

In Section II we give a summary of how directional coupling modulators are expected to operate and analyze the effect that constructional tolerances have on the quality of switching that may be obtained in actual devices.

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1. W. Phillips and J. M. Hammer, J. Electronics Materials 4, 549 (1975).
   J. M. Hammer and W. Phillips, Appl. Phys. Letters 24, 545 (1974).

Much of our work on this program has been reported in the three quarterly reports already submitted. We include here abstracts of the contents of these three reports.

In the first quarterly report [2] an approximate closed-form expression for the cut-off conditions and propagation characteristics of low-order modes in diffused Gaussian stripe waveguides is derived. The expression is given in terms of normalized diffusion depths and stripe widths and may be used to find the operating point of a $LiNb_xTa_{1-x}O_3$ stripe guide diffused from a Nb stripe of known thickness and width. An experimental $LiNb_xTa_{1-x}O_3$ "directional coupler" was fabricated by diffusing two 5-μm-wide, 800-Å-thick Nb stripes spaced 2 μm apart into a $LiTaO_3$ substrate. Reasonably efficient coupling of TM modes between the stripes is observed. The critical coupling length was estimated to be 0.13 cm by fitting the data from photodensitometer measurements of a photomicrograph to the expected sine-squared coupling characteristic. Additional discussion of the interpretation of observations of this type is given in Section V of this final report.

In the second report [3] the calculations of the properties of stripe guides of the first quarterly were extended to include calculations of the coupling coefficient, critical coupling length, and voltage behavior for diffused Gaussian stripe guides. A new technique for generating stripe guide couplers and other long narrow structures was described, based on the shadowing effect of *thick* slits placed between source and substrate during evaporation; the technique seems capable, with some refinement, of generating long narrow patterns of the type required.

In the third quarterly report [4] we discussed some of the experimental measurements made on passive directional couplers. These measurements were designed to help check the accuracy of the processing used in formation of these devices and indicated a large degree of uncertainty in dimensions caused by both the process used in forming the Nb patterns and in subsequent diffusion of these patterns. These observations are extended to help obtain dimensional tolerances in this final report.

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2. J. M. Hammer, W. Phillips and C. C. Neil, *Channel Waveguide Study*, Quarterly Report No. 1, Contract No. N00014-75-C-0078, March 1975.
3. J. M. Hammer, W. Phillips, and C. C. Neil, *Channel Waveguide Study*, Quarterly Report No. 2, Contract No. N00014-75-C-0078, June 1975.
4. J. M. Hammer, W. Phillips, and C. C. Neil, *Channel Waveguide Study*, Quarterly Report No. 3, Contract No. N00014-75-C-0078, September 1975.

II OPERATION AND ANALYSIS OF CONSTRUCTIONAL TOLERANCES OF DIRECTIONAL COUPLER MODULATORS

We consider the device shown schematically in Fig. 1. The operation of this type of coupling modulator, the development of which is the objective of this program, has been described in great detail in a number of places so we will only give the briefest outline. If β_1 is the propagation constant in guide 1 and β_2 that in guide 2, under phase match condition $\beta_1 = \beta_2$ and light will be coupled between the guides. If initially all the light is in guide 1 after traveling a distance, L, equal to the critical coupling length, all the light will be transferred to guide 2. If the interaction continues over a long length, light will be coupled back and forth between the guides.

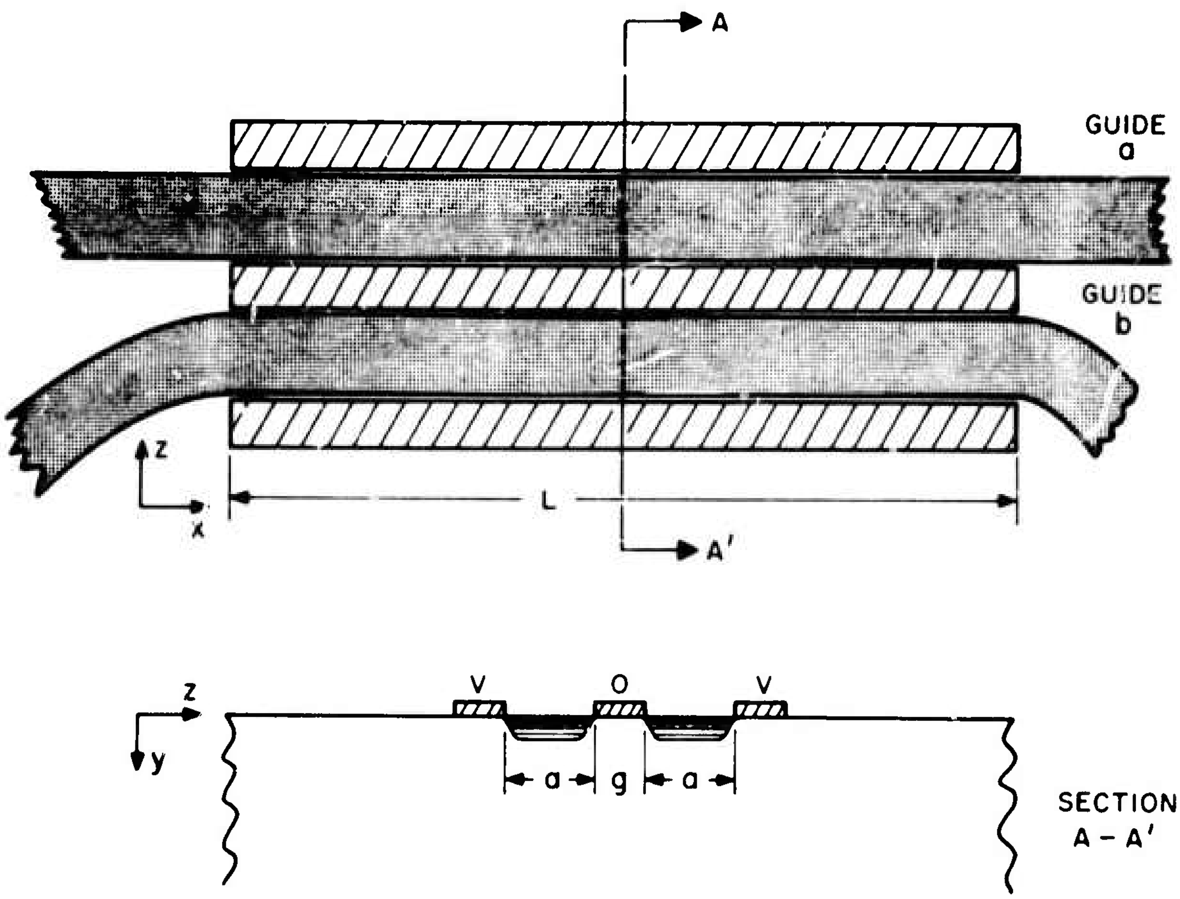

Figure 1. Schematic diagram of Type I push-pull stripe guide switch.

If $\beta_1 \neq \beta_2$, the amount of light coupled will be reduced and the coupling period shortened. The coupling is described by [5]

$$\frac{I_2}{I_o} = 1 - \frac{I_1}{I_o} = \frac{\kappa^2}{\kappa^2 + (\Delta/2)^2} \sin^2\left[\left(\sqrt{\kappa^2 + (\Delta/2)^2}\right)x\right] \tag{1}$$

where I_o is the intensity initially entering the coupling region and at $x = 0$, $I_2 = 0$, and $I_1 = I_o$. κ is the coupling coefficient and is related to the critical coupling length through

$$\kappa = 2/\pi L \tag{2}$$

Δ is a measure of the phase mismatch given by

$$\Delta = |\beta_1 - \beta_2| \tag{3}$$

Voltage applied to the electrodes shown in Fig. 1 changes Δ and for our geometry guides we have shown

$$\Delta \simeq \frac{2\pi}{\lambda_o} r' n'^3 \frac{v}{a} \tag{4}$$

where r' is the effective electro-optic coefficient and n' is the effective refractive index as defined in ref. [5]. Thus, a voltage can vary the amount of light coupled between the two guides.

The extinction ratio is defined by

$$\eta = \frac{|I_1 - I_2|}{I_1 + I_2} = \frac{|I_1 - I_2|}{I_o} \tag{5}$$

where the values of I_1 and I_2 are taken after the switch and a lossless system is assumed. Extinction ratios close to 1 (100%) are desired.

For the Type I device illustrated in Fig. 1, η will depend strongly on how closely the actual device length approaches the critical coupling length. The critical coupling length is proportional to the reciprocal of the coupling

5. J. M. Hammer, *Modulation and Switching of Light in Dielectric Waveguides*, Chapter IV of *Integrated Optics*, T. Tamir, ed., Springer Velag, New York, 1975.

constant which, in turn, is extremely sensitive to the device dimensions and propagation characteristics.

We will illustrate this sensitivity for the LNT type guide by using the closed form approximate theory derived in the first quarterly [2,6]. From this theory the coupling constant is given approximately by the expression

$$\kappa = \frac{n_2 \, \Delta n \sqrt{8A_1^2 - 1}}{8 \lambda_o AA_1^3 (n_2 + \delta n)} \exp \left(-\pi \frac{G}{A_1} \sqrt{8A_1^2 - 1} \right) \tag{6}$$

Where

$$A = \sqrt{n_2 \, \Delta n} \;\; a/\lambda_o$$

and

$$G = \sqrt{n_2 \, \Delta n} \;\; g/\lambda_o$$

$$A_1 = A + 0.2251$$

n_2 is the substrate index, Δn is the maximum difference in refractive index between the LNT guide and substrate, and δn is the difference in effective refractive index between the TE_{11} mode and the substrate. For our purpose δn may be neglected with little error. (δn may, however, be found from the theory given in the first quarterly report.)

Using Eqs. (6) and (2), L vs V for a variety of conditions is plotted in Fig. 2 which is reproduced from the second quarterly report. Quite obviously small changes in gap (g) or guidewidth (a) give rise to large changes in L. Since the design value of L is fixed by the pattern, these variations can result in poor extinction ratios.

In fabricating the stripe guide couplers, conventional photolithography is used in which Nb is deposited on a $LiTaO_3$ substrate, covered with photoresist and exposed through a mask. After development the Nb is etched leaving the desired pattern. The guides are then formed in a high temperature diffusion step. There are dimensional variations associated with the process of forming the Nb pattern, and there are further variations in material parameters and dimensions associated with the diffusion step. These variations

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6. J M. Hammer, Applied Optics, to be published Feb. 1976.

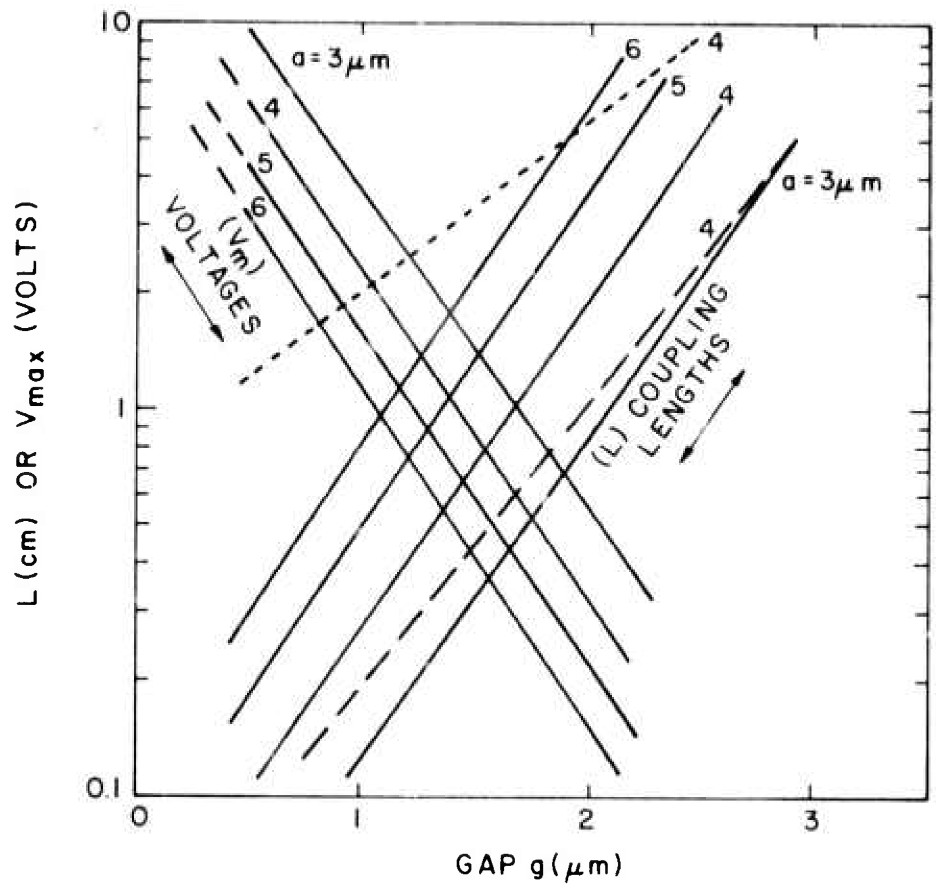

Figure 2. Critical coupling length (L) and shut-off voltage V_m vs gap g with stripe width (a) as parameter. The solid lines are for an initial Nb thickness (τ) of 0.08 μm and a diffusion depth (b) of 1.5 μm and values of (a) equal to 3, 4, 5, and 6 μm as labeled. The dotted line gives L vs g for the case b = 1.0 μm and a = 4.0 μm, and the dashed line for the case b = 2.0 μm and a = 4.0 μm. The strong dependence of L on all parameters should be noted.

are partly interrelated. In particular, the value of Δn is related to the initial thickness of Nb and the diffusion parameters (temperature and time). The effective depth and width of the resulting guide are related to both the original Nb dimensions and the diffusion conditions. Thus, variation in any of the processing steps will give rise to changes in Δn and in all the critical dimensions.

The Nb films are deposited using electron beam evaporation. The thickness is monitored with a Sloan thickness gauge. Because of variation in the sample position, the actual error in thickness is greater than the nominal capabilities

of the Sloan monitor, and we estimate that the thickness, τ, has been controlled in our equipment to $\pm 15\%$. We estimate that the diffusion depth, b, can be controlled to 7%. Since Δn = (constant) τ/b, the variations in τ and b give rise to an uncertainty in n of $\pm 17\%$. The other critical dimensions, namely, a and g, are controlled partly by the photolithography and partly by the side-wise diffusion spread. With fixed design centers, we feel that we can control the a and g dimensions to ± 0.25 μm if x-plates are used. The uncertainty with y-plates is much greater, as will be described later in this report. Using these uncertainties we calculate the range of variation in L from Eqs. (6) and (2). We pick nominal values; a = 6 μm, g = 0.5, 1 μm, τ = 0.08 μm, and b = 1.5 μm. Although the errors are not symmetric around the design center, if we round off, we obtain for the case g = 1.0 μm, L = 0.8 ± 0.56 μm, which is roughly a $\pm 70\%$ uncertainty. For the case g = 0.5 μm, L = 0.29 ± 0.22, or roughly a $\pm 75\%$ uncertainty.

These variation imply (see Fig. 2) that L can change by factors as high as 4 between extremes. It is clear that many samples of a Type I device would be have to be produced to obtain one sample with high extinction ratio.

An alternate approach that has been suggested by Zernike [7] to overcome the tolerance problem is to use an arrangement consisting of a 3-dB coupler, a phase shifter, and a second 3-dB coupler. This approach (referred to as a Type II coupling modulator) eases the tolerance requirement.

It is readily shown that if a fraction C_1^2 of the intensity is transferred by the first coupler and fraction C_2^2 by the second, the Type II device will have an extinction ratio of

$$\eta = \left(1 - C_2^2\right)\left(1 - C_1^2\right) + C_1^2 C_2^2 + 2C_1C_2\sqrt{1 - C_2^2}\ \sqrt{1 - C_1^2}\ \cos\left(\phi_1 - \phi_2 - \pi\right) \tag{7}$$

ϕ_1, ϕ_2 are the phase shifts between the two couplers in the first and second branches, respectively. For the ideal case $\phi_1 = \phi_1$ and $C_1^2 = C_2^2 = 1/2$; $I_1/I_o = 0$ and $I_2/I_o = 1$.

7. F. Zernike, OSA Tech. Dig. Integrated Optics (New Orleans, La.), Jan. 1974, paper WA5-1, and E. A. J. Marcatili, Bell System Tech. J. 46, 2093 (1969).

Thus, a phase shift $\phi_1 - \phi_2 = \pi$ will switch 100% of the light between the two guides if the couplers are accurately 50% (3 dB). If C_1^2 and/or C_2^2 vary from 1/2, then the extinction ratio will be reduced by an amount which is less than the shift in the coupling for moderate departures from 3 dB. This may be qualitatively seen in Fig. 3 where I_1/I_2 is plotted against C_1^2 for the three cases: $C_1 = C_2$, $C_2 = 0.51$, and $C_2 = 0.5$. In the worst case, $C_1^2 = C_2^2$, when $C_1^2 = 0.6$ $I_1 \simeq 0.04\ I_2$. We thus see that a 20% inaccuracy in both couplers only gives rise to a 4% reduction in extinction.

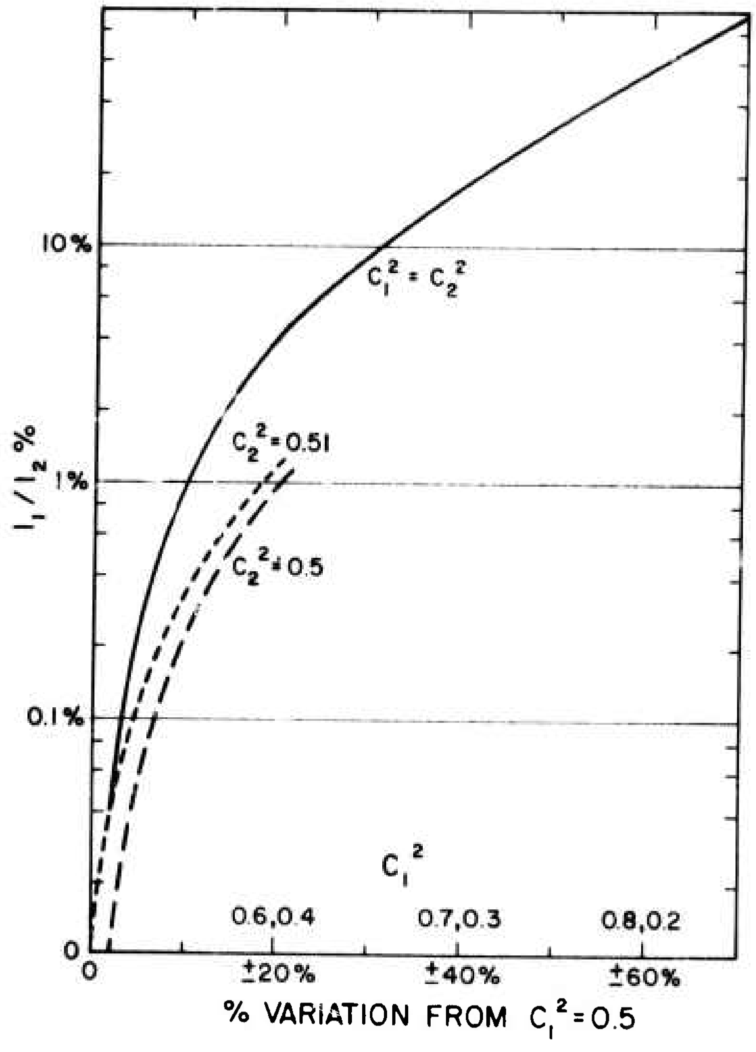

Figure 3. Variation in extinction ratio for Type II switch as the "3-dB" couplers vary from 0.5 (ratio).

Unfortunately, as we have just pointed out, we may have to expect uncertainties as high as 75% in simple phase-matched stripe guide devices. As can be seen from Fig. 3, for large departures from 50%, very poor extinctions are obtained and here the Type II device offers almost no advantage. Nonetheless, on the average, we would expect a better yield with the Type II device since the overall performance of switches with couplers that fall within 30% of nominal will be improved.

A possible alternative is to make active 3-dB couplers. That is, to use Type I electro-optic switches of reduced length to serve as the 3-dB couplers. It is readily shown that the "tuning" of this type of device covers the range 0.5L to 1.5L. This range is almost as large as our expected maximum variation. This approach, however, requires a more complex pattern with large lineal dimensions which strain standard photolithographic techniques.

III. MATERIAL STUDIES

Our characterization of LNT waveguides, until recently, has been based primarily on microprobe analysis of planar waveguide structures. The diffusion rate of Nb normal to the plane surface of $LiTaO_3$ substrates has been found to be about the same for all substrate orientations. It was therefore surprising to find that when stripe patterns were formed on $LiTaO_3$ y-plates, Nb diffusion in the plane of the surface was roughly 20 times as fast as it was normal to the surface.

This result is shown in Fig. 4. An electron microprobe beam has been scanned along the surface of a waveguide perpendicular to a stripe pattern.

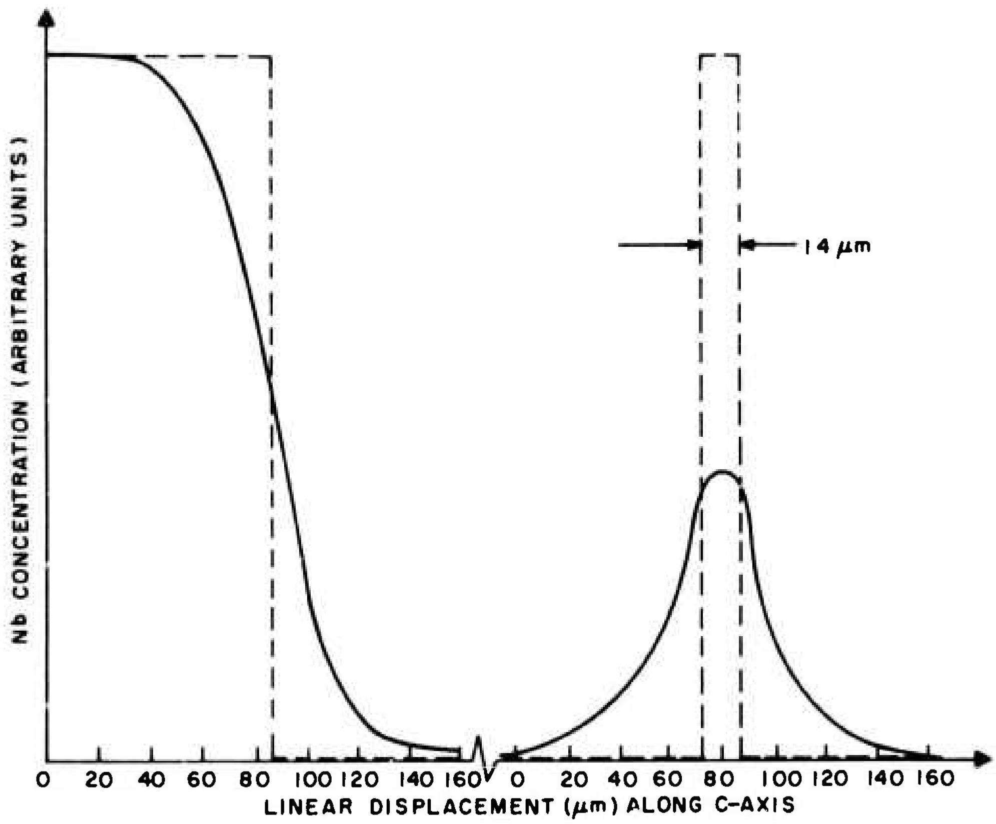

Figure 4. Distribution of Nb about the edge of a planar waveguide region (left) and a stripe of 14-μm nominal width (right). The stripe pattern ran perpendicular to the x-axis and was formed on a substrate cut perpendicular to the b-axis (i.e., a "y-plate"). The diffusion conditions (1100°C for 6 hours) were chosen to yield a 1-μm diffusion depth. The dotted lines show the position (inferred) of the initial metallic pattern.

The beam energy (25 keV) was sufficient to penetrate the entire waveguide thickness ($\sim$1.5 μm). Figure 4 shows the distribution of Nb found at the edge of a planar waveguide region and also the distribution about a stripe whose initial Nb width (a_o) is 14 μm. The sample used for this experiment had been coated with 800 Å of Nb and diffused at 1100°C for 6 hours. Under these conditions the depth of a planar waveguide is found to be 1.0 to 1.1 μm. In contrast, diffusion of Nb away from the stripe in the surface of the substrate is seen to be tens of microns. The distribution of Nb around the 14-μm stripe is roughly Gaussian, with a width to the i/e points of 51 μm. Subtracting the nominal width of the stripe and dividing by 2 gives a measure of the diffusion length in the plane. This number (19 μm) is roughly 20 times the diffusion depth (1 μm) for the sample.

A similar $LiTaO_3$ y-plate was prepared with stripes running parallel to the c-axis. The results of microprobe studies of two samples were quite similar, indicating that the in-plane diffusion is isotropic.

In contrast to the diffusion characteristics on y-plates, the diffusion of stripes formed on x-plates is comparable to the diffusion depth. This is illustrated in Fig. 5, which shows the microprobe characterization of the edge of a planar waveguide region and of a 14-μm stripe (running perpendicular to the x-axis) which were prepared identically to the sample in Fig. 4, except that these 14-μm stripes were formed on an x-plate. The apparent diffusion length associated with in-plane diffusion on this sample is 4 μm, or roughly four times the diffusion depth. The actual in-plane diffusion length may be smaller than 4 μm because the resolution of the microprobe analyzer has approximately this value.

A similar x-plate was prepared at a higher temperature to give a nominal diffusion depth of $\sim$1.4 μm. In this sample the measured in-plane diffusion length was about 5 to 6 μm, or about three times the diffusion depth.

The distribution of Nb about the stripes, particularly on y-plates, is markedly different from the physical appearance of the stripes. As reported earlier [8], formation of LNT stripes from an 800-Å layer of Nb is accompanied by the growth of a $\sim$2000-Å ridge on the surface of the substrate. This is the

8. W. Phillips and J. M. Hammer, *Waveguides in Lithium Niobate-Tantalate*, Final Report prepared for Office of Naval Research under Contract No. N00014-74-C-0320, September 1975.

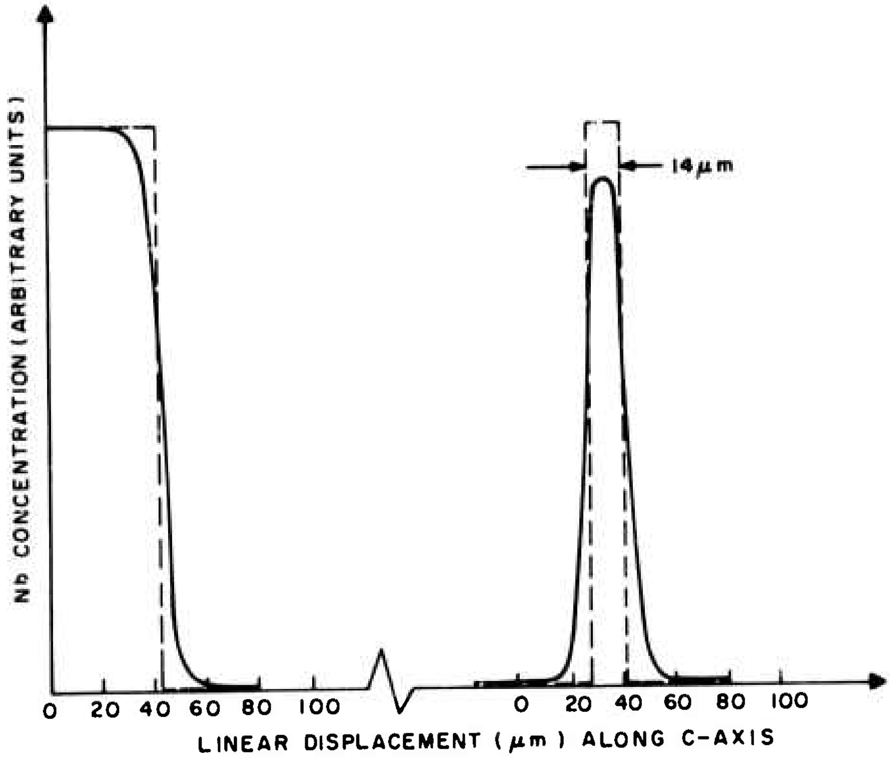

Figure 5. Distribution of Nb about the edge of a planar waveguide region (left) and a stripe of 14-μm nominal width (right). The stripe pattern ran perpendicular to the a-axis and was formed on a substrate cut perpendicular to the x-axis (i.e., an "x-plate"). The diffusion conditions (1100°C for 6 hours) were chosen to yield a 1-μm diffusion depth. The dotted lines show the inferred position of the initial metallic pattern.

amount of growth that would be expected if all of the Nb were converted to $LiNbO_3$ crystalline material during the diffusion process (as opposed to the Nb taking up interstitial lattice positions). The width of this ridge is essentially the same as the original metallic stripe. We present evidence in Section V that this ridge plays a role in the lateral confinement of light propagating in y-plate stripes.

To summarize, it appears that LNT waveguide formation involves the formation of new crystalline material with the composition $Li(Nb,Ta)O_3$ in the region under the metallic pattern, producing the observed growth ridge. This ridge persists, even though rapid diffusion of Nb parallel to the substrate surface quickly homogenizes the composition of the material under the ridge with that of the surrounding substrate.

IV. EFFECT OF SURFACE DIFFUSION ON PROPAGATION

The large surface diffusion length found in y-plates as described in Section III has a profound effect on the correct interpretation of our observations of guiding in y-plate stripe guides. The point of concern here is that for stripes of the sizes studied in this program (4 to 14 μm) the actual lateral distribution of refractive index of a y-plate after diffusion is controlled mainly by the surface diffusion length. The effect of initial width is, however, shown in two other ways. First, since there is a fixed amount of niobium available which depends on the width and thickness before diffusion, the maximum index difference between stripe and substrate, Δn_s, varies with the initial stripe width. Second, there is a raised "ridge" of LNT with width close to that of the initial stripe and height equal to approximately twice the initial niobium thickness. The first effect results in a strong reduction of the maximum index difference between the stripe and the substrate when compared with the index difference for a similarly prepared planar LNT guide. If the index difference in the planar case is Δn_p, the reduction factor $\Delta n_s/\Delta n_p$ may be inferred from the microprobe studies described earlier. A plot of $\Delta n_s/\Delta n_p$ against initial (nominal) niobium stripe width a_o (see third quarterly) is given in Fig. 6. There is almost a linear increase in $\Delta n_s/\Delta n_p$ with increasing a_o and, as might be expected, this factor approaches 1 as the initial stripe width approaches a surface diffusion length. Figure 6 may be used to interpret our observation of cut-off in y-plate stripe guides and will be discussed below in that context.

The effect of the ridge is much harder to understand. At this point we do not have any theoretical analysis available for the case of a ridge superimposed on a diffused guide. Clearly, for the case of narrow initial stripes which yield very small values of Δn_s after diffusion, the ridge might be adequately described as a ridge in a single material waveguide. Theories even for this case are not available. It is our opinion that both the ridge and Nb distribution play significant roles in determining the guiding characteristics.

The effect of surface diffusion on our attempts at making directional couplers using y-plates is as follows. The refractive index distribution, ignoring the projecting ridges, is that of a single guide of width before

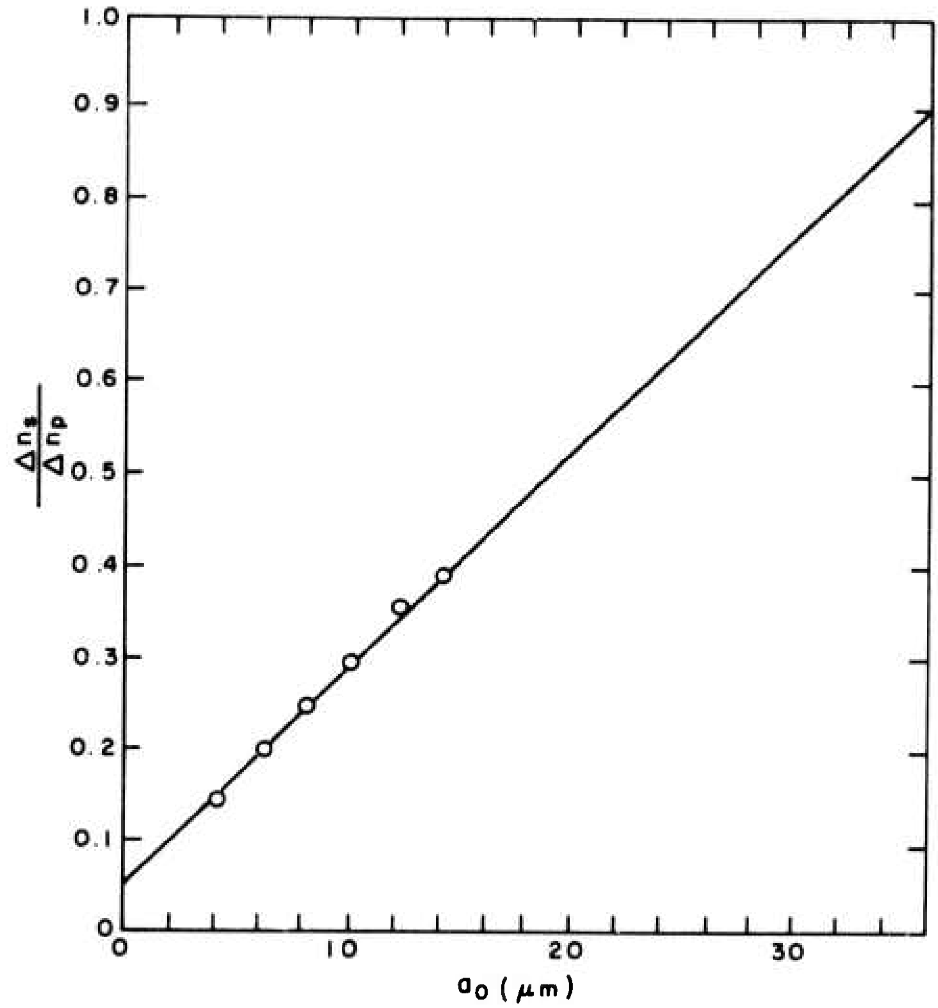

Figure 6. Reduction factor $\Delta n_s/\Delta n_p$ vs nominal stripe width a_o.

diffusion slightly less than the sum $2a_o + g$. After diffusion the overall width is in the range of 30 to 40 μm, and the gap cannot be distinguished in the Nb distribution. The observations of directional coupling described in the first quarterly report [2] are probably due to the presence of the ridges.

The question of the effect of applied electric field must be answered by further study. In principle, however, with the arrangement used here the field effect can as well be described by a decoupling of modes as by a decoupling of guides.

The microprobe studies on x-plates indicate that the surface diffusion is on the order of only a few times the bulk diffusion and that stripe guides can be obtained with after-diffusion dimensions reasonably close to the initial Nb width. Unfortunately, our recognition of the full implication of the surface diffusion came very late in the program and serious studies of stripe guides on x-plates have just been undertaken.

It is clear, however, that well-controlled LNT stripe guide devices will have to be made on x-cut plates. The tendency of these plates to fracture can be avoided by proper selection of the boule growth direction.

V. EXPERIMENTAL STUDY OF PROPAGATION CHARACTERISTICS

The principle tool used in our study of the propagation characteristic of LNT stripe guides is the "ladder" array of stripes of varying width formed on a common substrate illustrated in Fig. 7. As can be seen, a series consisting of stripes with pattern widths of 4, 6, 8, 10, 12 and 14 μm (not in this order) is formed. Each stripe is connected at both ends to a region of planar guide by a simple linear horn with an included angle of 14°. This rather large angle has proved adequate for coupling a reasonable fraction of light from the planar guide region to the stripes if a well-focussed beam enters the planar region from a prism coupler. Both the input and output prism couplers are positioned so that light can be coupled into all the stripe guides and into a region of planar guide by simply moving the laser parallel to y (see Fig. 7). The ladder structure thus allows the propagation characteristics of stripe guides of varying widths to be compared with each other and with the propagation on a planar guide. All the parameters except the width (a_o) are identical since the guides share a common substrate, identical initial niobium thickness, and diffusion parameters. Measurement of the output light gives a measure of the loss which can be compared with the planar waveguide loss of the adjacent planar region. Thus, an upper bound on the cut-off width of the stripes can be found.

The results of measurements made on a ladder structure formed to run parallel to "c" on a y-plate are shown in Table 1. For this sample the initial niobium thickness τ is 800 Å. The diffusion temperature T is 1100°C and the diffusion time t is 6 h. These values give a planar waveguide depth of b = 1 μm and, using Eq. (14) of the first quarterly, a planar Δn of 0.0306. As can be seen, propagation is observed through the planar region and through the a_o = 14, 12, 10, and 8 μm stripes. No light passes through the a_o = 6 and 4 μm stripes. Because of sideways diffusion, we expect the planar value of Δn = 0.0306 to be reduced for the stripes, and, using Fig. 6, we include the expected values of Δn in the table. Our theory [2] predicts that planar guides with normalized coordinate B below 0.229 will be cut off so that, from the table, we would have expected that the 8-μm guide would be cut off in addition to the 6- and 4-μm guides. We might perhaps be tempted to attribute the discrepancy to the presence of the ridges, but we think it is as likely that we are within the limits of accuracy of our simple theory.

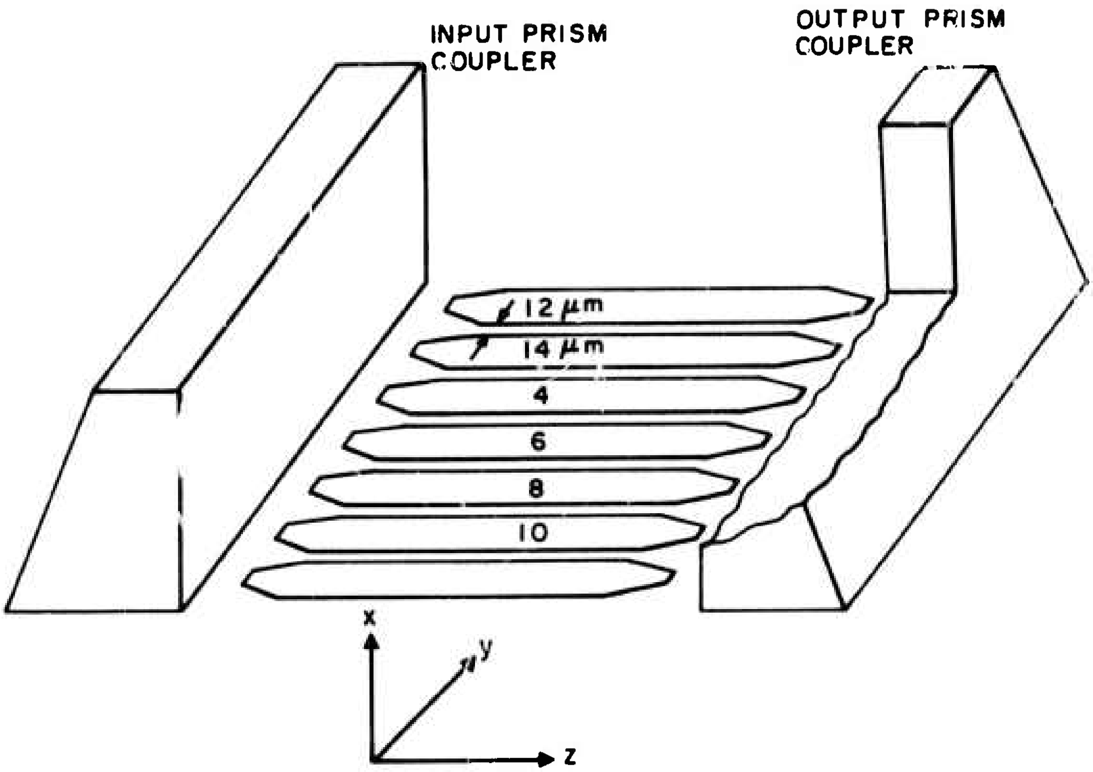

Figure 7. Schematic perspective view of ladder array of stripes of varying widths.

TABLE 1. RESULTS OF MEASUREMENTS ON LADDER STRUCTURE

y plate || to "c"

τ = 800 Å T = 1100°C t = 6 h b = 1
I_p = output intensity through planar guide
I_s = output intensity through stripe guide

$a_o/\mu m$	I_s/I_p	Δn	$B = \sqrt{n \Delta n}\ b/\lambda_o$ *
∞ (planar)	1.0	0.0306	0.408
14	0.089	0.0129	0.265
12	0.054	0.0124	0.260
10	0.024	0.0097	0.230
8	0.015	0.0082	0.211
6	0.000 } Cut-off	0.0066	0.189
4	0.000 } Cut-off	0.0049	0.163

*Δn found from Fig. 6 using Eq. (14) of first quarterly [2]. The theory given in the first quarterly predicts that planar LNT guides will be cut off for values of B below 0.229.

In the second sample with identical processing parameters the stripes are arranged to run at right angle to the "c" direction giving a maximum B value for all stripes below 0.229, and indeed no propagation is found in this sample (03208 B).

The observation of the diffraction spread of light prism coupled out of the stripe guide coupler reported in the third quarterly report [4] has to be reinterpreted in view of our present understanding of the surface diffusion. In the third quarterly, an effective sideways spread of approximately twice the diffusion depth was assigned to a sample formed on a y-plate (sample 35175 S) on the basis of diffraction observations. These observations seem hard to justify if we assume that the effective stripe width is entirely determined by the post-diffusion distribution of Nb without regard to the ridge. If, however, the niobium distribution normal to the surface serves to restrain the light from coupling down to the substrate (a restraint expected in the case of diffusion from two adjacent 5-μm Nb stripes), then the ridge may well serve to confine the light laterally. As mentioned earlier, the condition of theoretical understanding of this complex guiding system is not adequate to make these determinations. The observations in the third quarterly on sample 35196 S, an x-plate, are consistent with our measurements of lateral diffusion and require no further elaboration.

A. STRIPE GUIDE MODULATOR ELECTRODES

The dimensions of the electrodes which were used in our attempts to observe electro-optic modulation of the stripe guide "couplers" are shown in Fig. 8. As mentioned, our attempts to position the electrodes using a lift-off technique failed. We were, however, successful in forming the electrodes using conventional photolithography in which the electrode pattern is finally formed by etching. A detailed description of the procedure is given in Appendix A.

We found that the ridges which formed on the stripe guides gave good contrast when covered with the required chrome gold so that the mask for the electrode pattern could be positioned using a standard alignment microscope.

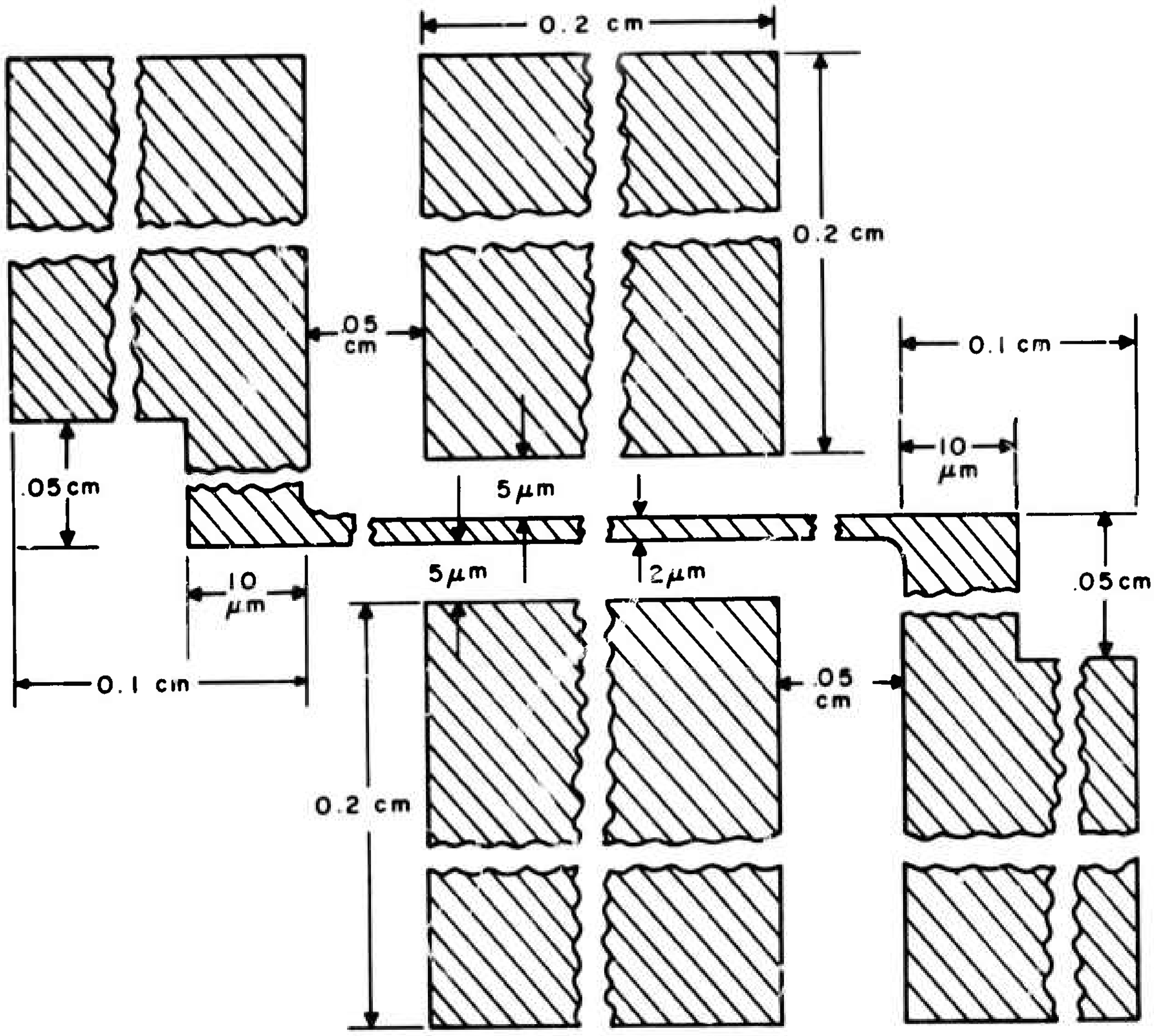

Figure 8. Dimensional drawing of electrodes for electro-optic modulation of stripe guide couplers.

Portions of a successfully formed electrode structure is shown in Fig. 9 under 500X magnification. The center electrode and the stripe guides can readily be seen. A common problem is that our etching causes the opens seen in the center electrode of Fig. 10. Here the magnification is 100X so that a portion of the center electrode connecting bus and pad is visible.

Electrodes were placed on three samples of stripe guide couplers formed on y-plates. In one sample, the second tried, complete shut-off of the light coupled out of the exit prism was observed at an applied voltage of approximately 10 V. This observation could not be repeated the next morning, and it was found that a number of opens had formed in the 2-μm center electrode.

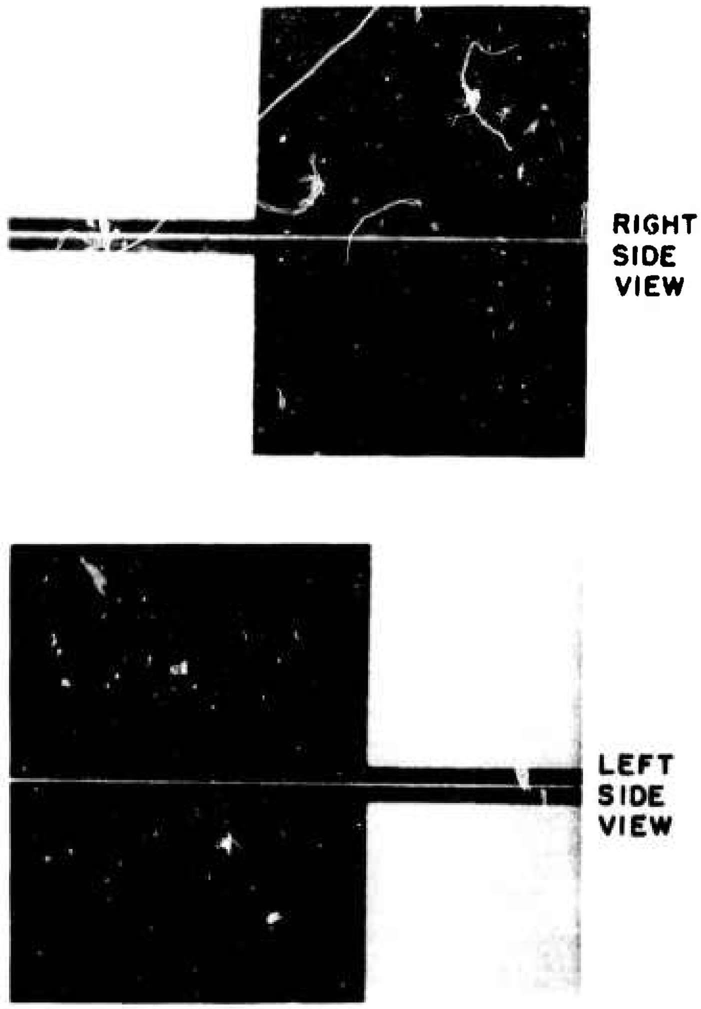

Figure 9. Photomicrograph of electrodes (500X).

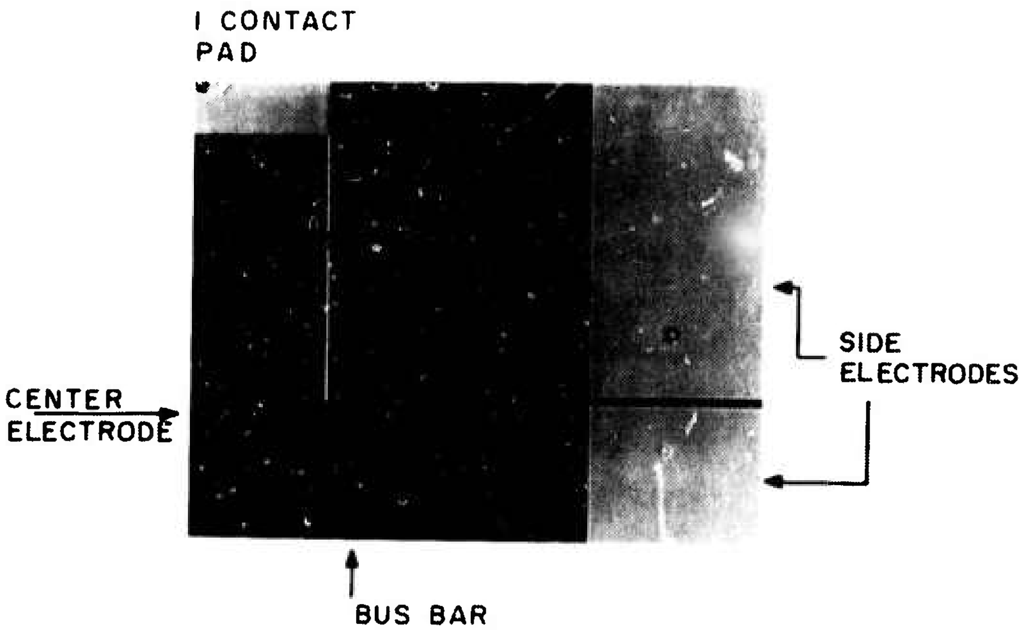

Figure 10. Photomicrograph of electrodes (100X).

No modulation was observed in the first and third samples. Here, too, microscopic examination of the center electrode made after voltages up to 30 V had been applied showed a number of opens. Thus, our failures to date are apparently due to a breakdown of the center electrodes. The opens are concentrated in the region where the center electrode enters the gap between the two side electrodes and appears to be due to the formation of an arc between the sharp corners of the side electrodes and the center electrode. We think this problem can be alleviated by rounding the sharp corners of the side electrodes and/or covering the electrodes with an insulating layer. Additionally, we have been forming the electrodes using only 500 Å of gold which makes them easily damaged. 1000 Å of gold can be used and should result in electrodes which are more resistant to arc damage. Finally, for the dc and low frequency operation used in initial measurements, the insertion of a series resistor will tend to limit arc energy and prevent damage.

We are actively pursuing these measures at the present time but do not have results available in time to be included in this report.

B. CONCLUSION

As a result of our studies under the present contract, we have formed a number of passive stripe guide couplers in LNT. The interpretation of the operation of these devices depends on whether they have been constructed on x- or y-plates. With y-plates our observation of large lateral diffusion indicates that we are dealing with what may perhaps be better described as multimode guides. The interpretation of x-plate data is less ambiguously identified as coupling between two guides.

Our studies of the mechanism of diffusion remain incomplete and provide an important area for future research.

Our observation of the formation of a ridge taken in conjunction with the large lateral diffusion on y-plates and the restricted lateral diffusion on x-plates points out the need for additional theoretical understanding of the operation of stripe guide couplers with a ridge configuration.

We have developed a useful approximate theory for the operation of diffused stripe guide couplers and modulators which, as far as we know, is the only closed form theory available for devices of this type. Using this theory, we have been able not only to again point out the high sensitivity of this class of devices to dimensional tolerances but also to give semi-quantitative limits which are not available in the literature.

Finally, we have a preliminary indication that the coupler can be electrically controlled and we have identified the chief source of failure in our electro-optic experiments. The arcing problem can be overcome in a number of ways and is not fundamental.

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APPENDIX A

PROCESS FOR MARK I ELECTRODE DEPOSITION ON STRIPE GUIDES

1. Standard cleaning process.
2. Evaporate 50 Å Cr 1000 Å Au.
3. Spin on AZ 1350 B pos. working photoresist at 3000 rpm for 40 seconds. Bake on hot plate for 1 hour at 90°C.
4. Visually aligned 3-mm-long electrode and exposed UV lamp 12.5 seconds.
5. Developed in 1-1 mix of AZ 1350 developer and water for 14 seconds. Post bake on 65°C hot plate for 15 minutes.
6. Etch for 6 seconds in C-35 conductor etch. Rinse in water.
7. Soak 15 minutes in acetone to remove photoresist.
8. Etch for 15 seconds in chrome etch made up of 1-to-1 mix of KOH and K_3FeCn_3.